NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3377

FLIGHT MEASUREMENTS OF THE VELOCITY DISTRIBUTION AND PERSISTENCE OF THE TRAILING VORTICES OF AN AIRPLANE

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SUMMARY

The disturbance created by the trailing vortices of an airplane can have a detrimental effect on the flight of another airplane passing through the wake. An attempt has been made, therefore, to measure the velocity distribution and persistence of the trailing vortices of a propeller-driven fighter-type airplane. This airplane was equipped with a smoke-generating device to mark the vortices in the atmosphere. A jet airplane having a high-frequency angle-of-attack vane and a sensitive total-pressure instrument was used to fly through the vortices.

In general, the vortex strength did not decrease appreciably up to 35 seconds after the vortices had been shed. After 35 seconds and up to 60 seconds (the largest time interval measured), the vortices gradually deteriorated, but the velocity distribution indicated that a large amount of circulation still remained in the vortex pair. The velocity distributions showed no indication of a disturbance other than that produced by the trailing vortices. Photographs of the trailing-vortex filaments indicated that they did not remain straight but became irregular as a result of atmospheric turbulence. In an attempt to fly in the trailing wake of another airplane, the pilot found that it was very difficult to maintain a precise course and that the disturbance was similar to severe turbulence.

INTRODUCTION

The trailing wake left by an airplane as it travels through the atmosphere is known to contain a large amount of turbulence. Many accidents have occurred as a result of this turbulence, especially to light airplanes, during the landing approach where one airplane follows another onto a landing strip (ref. 1). Accidents resulting in failure of the horizontal tail have also been experienced by high-speed fighter-type airplanes while making bombing or strafing runs. In such flights as these, the airplanes follow one another at relatively high speed and under high accelerations. The cause of these accidents has been suspected to be turbulence in the wake of a preceding airplane which produced added loads on the horizontal tail sufficient to cause failure. The effects of the wake of an airplane on the course of a guided missile or an automatically controlled interceptor airplane have also become important because the effectiveness of these weapons depends largely on their ability to maintain a precise course.

The turbulence created by the trailing vortices of an airplane is known to contain large amounts of energy. The theoretical solution for the strength and velocity distribution in these vortices has been known for some time (see ref. 2). Theoretical investigations of the rate of decay of these vortices considering the viscosity of air have also been made (ref. 3). The theory indicates that the vortices may persist for periods of 30 minutes or longer, depending upon their initial strength. The effects of normal atmospheric conditions on the vortices, however, have not been established. The purpose of the investigation reported in this paper is to attempt to measure experimentally the velocity distribution and persistence of the trailing vortices of an airplane under normal atmospheric conditions.

APPARATUS AND TESTS

Apparatus

A jet airplane was used to penetrate the trailing vortices created by a small propeller-driven fighter airplane. An angle-of-attack vane, an airspeed head, and an additional total-pressure tube were located on a boom at the nose of the jet airplane. A photograph of this installation is shown as figure 1. Inasmuch as the same jet airplane was not available for all the tests, two similar jet airplanes were used, but only one was used in any given test. The instrumentation described for the penetrating airplane was interchangeable in the two jet airplanes. The pertinent dimensions of the three airplanes used in the tests are presented in table I.

The angle-of-attack vane used to obtain the vertical velocity component of the vortices was designed to have a relatively high natural frequency to insure a fast response and to have the characteristics necessary to reproduce the angle-of-attack change to be expected from the trailing vortices. The vane used had a natural frequency of 44 cycles per second at a forward speed of 200 feet per second at sea level and a damping ratio of 0.55 of critical. These characteristics were determined from wind-tunnel tests of the vane. The system used to record the vane angle had a natural frequency of 105 cycles per second and a damping ratio of 0.65 of critical. The measurements of the vane and recording system were accurate to within $\pm 0.18^{\circ}$.

In order to obtain the horizontal velocity component of the vortices, a sensitive total-pressure system capable of measuring ±5 inches of water was used. One side of the pressure cell was connected by means of 100 feet of tubing to the total pressure of the airspeed head. This pressure source was used as a reference pressure. The other side of the pressure cell was connected to the total-pressure tube on the nose boom by means of a relatively short piece of tubing. A schematic drawing of this installation is presented in figure 2. The 100 feet of 1/16-inch-inside-diameter tubing resulted in an acoustic lag of about 0.2 second and a viscous lag with a time constant of about 3.9 seconds on the reference side of the sensitive cell. This means that, for the first 0.2 second following a change in total pressure, the reference pressure did not change, and after this time the reference pressure changed slowly in accordance with the time constant of the system. The 0.2-second acoustic lag was desirable because the time required for the test airplane to fly through the vortices at the test speed of about 400 feet per second was approximately 0.2 second. Because of the acoustic lag and the additional viscous lag, the changes in pressure measured by the sensitive cell were considered to be due entirely to the effects of the trailing vortices. The pressure-measuring system just described had an estimated accuracy of ±0.025 inch of water.

The normal acceleration, pitching velocity, airspeed, and pitch attitude of the airplane passing through the vortices were also recorded. All the instruments were synchronized with a 0.1-second timer. The film recording speed was 4 inches per second. This high film speed was used in an attempt to record any sudden changes in the quantities being recorded.

The airplane used to create the vortices was equipped with a smoke-generating device to mark the vortices in the atmosphere. A tank containing about 1 gallon of titanium tetrachloride was located in each wing. These tanks were pressurized with dry nitrogen at 10 pounds per square inch. A tube containing a solenoid-operated valve was run from each of the tanks to the corresponding wing tip so that the liquid could be dispelled into the vortices. A switch located in the cockpit allowed the pilot to control the passage of the liquid. A photograph of the wing-tip installation of the smoke-generating airplane is presented as figure 3. In addition to the smoke-generating equipment, the airplane was instrumented to measure and record the airspeed and normal acceleration of the airplane.

Tests

Before beginning a given series of tests, the pilot of the penetrating airplane would perform a gunnery run on the smoke-generating airplane at the same speed and altitude at which the tests were to be made and adjust his gunsight so as to correct for the attitude of the airplane. This procedure aided the pilot in penetrating the center of the smoke trail.

The tests were conducted in the following manner. The smoke-generating airplane would fly straight and level at 150 miles per hour at an altitude of 10,000 feet and usually in what could be termed smooth air. The pilot would release the smoke-producing liquid in about 3- to 5-second bursts, which produced a smoke trail of approximately 1,000 feet. The pilot of the penetrating airplane would then fly a course perpendicular to the path of the smoke-generating airplane and attempt to penetrate the trail. A different smoke trail was utilized for each test. During the tests the pilot of the penetrating airplane attempted to maintain level flight and penetrate the vortices containing the smoke along a line joining the center of the two vortex filaments. In order to ascertain the time after release that the penetrating airplane entered the vortices, the pilot of the smoke-generating airplane recorded the time of smoke release and the pilot of the penetrating airplane recorded the time of penetration and relative position along the smoke trail. It is estimated that this method resulted in an accuracy of about ±3 seconds with regard to the time after release that the vortices were penetrated. The procedure just described was used to penetrate the vortices at various lengths of time after the vortices were generated so that the persistence of the vortices in the atmosphere could be determined.

In order to study the general pattern of the trailing vortices in the atmosphere, motion pictures were taken both from the ground and in the air of the smoke trail which marked the location of the vortices. The pictures taken in the air were photographed from a helicopter. For these tests, the airplane generating the vortices flew at an altitude of about 1,000 feet in order to simplify the photographing operation.

REDUCTION OF DATA

The vertical velocity component of the flow in the vortices as measured by the angle-of-attack vane of the penetrating airplane can be expressed by the following equation; in this equation all angles are assumed to be small variations from the steady state and the trigonometric functions have been replaced by the values of the angles in radians:

$$w = V(\Delta\delta_v - \Delta\theta) + l\,\Delta\dot{\theta} + \int a_n\,dt$$

where

w	vertical velocity component of vortices, positive up, ft/sec
V	true forward speed of airplane, ft/sec
$\Delta\delta_v$	change in vane angle, positive up, radians
$\Delta\theta$	change in pitch angle, positive up, radians
l	distance from airplane center of gravity to angle-of-attack vane, ft
$\Delta\dot{\theta}$	change in pitching velocity, positive up, radians/sec
a_n	normal acceleration, positive up, ft/sec^2
t	time, sec

In the preceding equation, the forward speed of the airplane was assumed to remain constant during the passage of the airplane through the vortices. This assumption neglects the effects of the horizontal velocity component of the vortices. The horizontal velocity component of the flow in the vortices was obtained directly from the sensitive total-pressure tube previously described. A time history of a particular test run which is typical of the data obtained is shown in figure 4. The pitching velocity in this particular case resulted in a vertical velocity component of about 2 feet per second at some periods during the test run. In most of the test runs, however, the vertical velocity component resulting from the pitching velocity and normal acceleration was relatively small, on the order of 0.5 foot per second or less, and was usually neglected. It should be noted in figure 4 that, after the second vortex center was reached, the angle-of-attack vane oscillated. This oscillation is a result of the excitation of the first bending mode of the wing which forces the boom housing the angle-of-attack vane to oscillate at the same frequency. The wing structural frequency is evidently excited by the sudden change in lift as the wing passes through the region of the first vortex center. Because of this oscillation, the data beyond the region of the second vortex center are considered unusable and have been deleted from the velocity-distribution data presented. The vertical and horizontal velocity components of the vortices as obtained from the vane-angle and total-pressure records and the appropriate contributions of the pitching velocity and normal acceleration shown in figure 4 are presented in figure 5.

The velocity distribution of the vortices along the path followed by the airplane was determined in the following manner. The first point at which the change in vane angle became zero after a sudden change was, for purposes of orientation, used as a reference point. The time scale of both the horizontal and vertical velocity components was then converted to a distance in feet from this reference point by multiplying the time increment by the forward speed of the airplane. The vertical and horizontal velocity components at various distances from the reference point were then plotted and a resultant velocity was obtained. This process is illustrated in figure 6 where the horizontal and vertical velocities in figure 5 have been used to obtain the velocity vectors shown. In the region of the vortex centers, where the velocity is relatively high, the effect of one vortex on the other is small and in this particular analysis has been assumed to be negligible. In the vicinity of the vortex centers, therefore, the location of the vortex center can be found by drawing lines perpendicular to the resultant velocities and determining their point of intersection. In some instances the center of both of the vortices could be obtained and the flight-path angle followed by the penetrating airplane as it passed through the vortices could be located by drawing a line between the two vortex centers. This angle could then be compared with the angle measured by an attitude recorder in the airplane to provide a check on the method used to obtain the vortex centers and the subsequent velocity distribution.

After the approximate location of the first vortex center was determined, the distance from each of the resultant velocities to this center point was obtained and a plot made of the velocity distribution of the vortices. The velocity distribution obtained from the data in figure 6 is shown in figure 7. This velocity distribution can be assumed to be fairly close to one that would be obtained along a line joining the two vortex centers. It should be noted that the procedure described can be used only when the airplane flight path passes relatively close to the centers of the two trailing vortices.

RESULTS AND DISCUSSION

The results obtained from flight test surveys of the trailing vortices of an airplane are presented in the form of velocity distributions in the vortex pair and photographs of smoke contained in the vortices. Figure 8 presents typical velocity distributions for various lengths of time after vortex separation. Photographs of the vortices as marked by smoke in the atmosphere are presented as figure 9. Because the relatively small amount of data obtained prevents a statistical analysis and because of the general irregularity of the trailing vortices, no quantitative analysis of the strength or persistence of the vortices in the atmosphere can be presented. The irregularity or distortion of the vortices is readily obvious from the photographs of figure 9. Some general statements can be made, however, which should be of interest to those concerned with disturbances resulting from the turbulence created by the passage of an airplane through the atmosphere.

From the data obtained, the strength of the vortices appeared to change very little for times after separation up to about 35 seconds (see figs. 8(a) to 8(e)). The velocities measured for the different times varied, of course, but generally the shapes of the velocity distributions were similar and it might even be noted that the highest velocity measured was obtained 33 seconds after the vortices had been shed. After this time, the vortex strength gradually decreased up to 60 seconds after separation, the longest length of time measured. At 60 seconds, the vortices still maintained a relatively large amount of circulation (see fig. 8(h)). Attempts were made to obtain data at longer lengths of time, but the density of the smoke injected into the vortices began to deteriorate rapidly after about 60 seconds and the pilot could not locate the vortices. It is probable, however, that the vortices would persist for considerable lengths of time after 60 seconds under favorable conditions, but, as would be expected, turbulence in the atmosphere has a large effect on the persistence of the trailing vortices. The times noted, which indicate the length of time after the trailing vortices were shed, become more impressive from the standpoint of persistence when the distance traveled in this length of time by the airplane producing the vortices is considered. For instance, an airplane flying at an altitude of 10,000 feet at a Mach number of 0.8 will travel approximately 5.2 miles in 30 seconds. The data indicate that after 30 seconds the vortex strength will have decreased very little under good weather conditions.

In comparing the measured characteristics of the trailing vortices with those predicted by theory, several observations can be made. The basic theory (ref. 2) for the circulation Γ in a perfect fluid is expressed by the following equation:

$$\Gamma = \frac{L}{\rho V} \tag{1}$$

where

Γ	circulation, sq ft/sec
L	lift per unit span, lb/ft
ρ	density, slugs/cu ft
V	true airspeed, ft/sec

and the tangential velocity of each vortex is

$$v = \frac{\Gamma}{2\pi r} \tag{2}$$

where

v tangential velocity, ft/sec

r distance from vortex center, ft

These fundamental expressions indicate that the velocities near the vortex center approach infinity as the radius approaches zero. This result is known to be in error for a viscous fluid and the results of these tests give an indication of the size of the core of the trailing vortices. A summary of the data indicates that a maximum velocity is reached at a radius of 2 to 5 feet after which, as the radius approaches zero, the velocity decreases suddenly and a region exists where the velocity becomes proportional to the radius.

Another interesting point is the distance between the two trailing vortices. The theory indicates that the vortex centers will be a distance $\pi/4$ times the span apart for an elliptical span loading after the wing vortices have rolled up into two discrete vortices (see ref. 4). This distance for the test airplane, that is, $\pi/4$ times the span, is 29.3 feet. The test results indicate that the distance between the vortex centers is about 29 to 30 feet, which substantiates the theory. In general, the shapes of the velocity-distribution curves obtained from the tests are as to be expected from theoretical considerations.

The turbulent wake left by an airplane in the atmosphere is sometimes thought to be the result of the wake of the propeller or, in the case of a jet airplane, the wake due to the jet exhaust. The data obtained in these tests indicate that for any appreciable distance behind the airplane creating the turbulence, on the order of 1,000 feet or more, the conception of so-called "prop wash" is erroneous. The velocity distributions show no indication of a disturbance other than that produced by the trailing vortices. There are several facts which tend to corroborate this conclusion, the foremost of which is the relative strength of the energy imparted to the air by the thrust of an airplane as compared with the energy contained in the trailing vortices as a result of the lift. The relative size of the lift and thrust forces is indicated by the lift-to-drag ratio, which, for a fighter-type airplane, is on the order of 10:1 to 15:1. This ratio is, of course, higher for a transport- or bomber-type airplane. The mass of air affected by the thrust is also relatively small and at the same time dissipates at a high rate because of the high initial velocities imparted to the air.

The photographs presented in figure 9 were made in an effort to study the general pattern of the trailing vortices. Turbulent weather conditions prevailed during the filming of these pictures. The vortices were generated at 200 miles per hour at an altitude of about 1,000 feet where the wind velocities were about 20 to 25 miles per hour. The pictures shown are time sequences of the trailing vortices from the time they were generated to a time about 30 seconds later. These pictures are prints made from a motion-picture film obtained from a camera located on the ground. The camera was moved during the filming of the pictures so that the clouds or some other point in the picture had to be used as a reference in order to determine the time that the vortices had been in the atmosphere. Since the fuselage length and the airspeed of the airplane in the pictures are known, an approximate time scale can be determined for a given picture size. This information, together with a knowledge of the film speed, was used to determine the time scale shown in the pictures.

The vortex filaments remained straight for about 3 to 4 seconds, but after this time the turbulence in the atmosphere distorted the wake such that the trail was displaced in a random manner. This random nature of the trailing wake of an airplane would create a difficult medium for an airplane attempting to maintain a precise course. That is, an airplane trying to fly on or near the course of another airplane would be continuously flying in and out of the trailing vortices. The random nature of this disturbance would be expected to have a detrimental effect on an airplane or a missile attempting to attack another airplane from the rear since the disturbance would be similar to flight in severe turbulence.

One attempt was made to fly a jet airplane behind another jet airplane to measure qualitatively the effects of the wake on the flight of the following airplane. The pilot reported that when he encountered the wake region it was very difficult to maintain a precise course because the disturbance was similar to severe turbulence. The increase in normal acceleration due to the wake appeared to be small, but the rolling motions of the airplane were large and uncontrollable, and large aileron deflections were required to maintain trim.

In any discussion involving the effects of the trailing vortices, such as the effect of one aircraft following another, the magnitude of the circulation involved should be considered. This point should be emphasized for the data presented in this report because of the relatively small size of the airplane which created the vortices. By combining equations (1) and (2), the following relationship can be established:

$$v = \frac{W/b^2}{2\pi\rho V\frac{r}{b}} \qquad (3)$$

where

W weight, lb

b wing span, ft

From this equation for a single vortex, the velocities in the vortex are seen to be directly proportional to W/b^2 for given values of airspeed, altitude, and ratio of radius to span. Based on equation (3), calculations were made for a typical transport airplane by using the data obtained for the test airplane that is presented in figure 7. The transport was assumed to have a gross weight of 125,000 pounds and a wing span of 118 feet, which resulted in a value of W/b^2 that was 1.46 times the value of W/b^2 for the test airplane. The calculations were made for the same airspeed and altitude as the test airplane. Because the analysis made is directly dependent upon the relative spans of the two airplanes considered, it should be noted that the span and core diameter of the vortices are assumed to be directly proportional to the wing span. The data thus obtained are presented in figure 10. This figure illustrates the effect of airplane size on the velocity distribution in the trailing vortices. The velocities of the transport are considerably increased and the area covered by the vortices is much greater than that of the test airplane. The effects of this disturbance on another airplane penetrating the wake of the transport would be expected to be much more severe than those associated with the smaller airplane.

CONCLUDING REMARKS

The velocity distribution and persistence of the trailing vortices of an airplane have been measured in flight by flying a jet fighter airplane through the wake of a propeller-driven fighter airplane. No definite conclusions as to the persistence of the trailing vortices can be reached because of the limited data, but some general remarks can be made.

The strength of the vortex pair did not decrease appreciably up to about 35 seconds after the vortices had been shed. Variations occurred in the shapes of the velocity distributions obtained, but the maximum velocities in the region of the vortex core were in the same range. The vortex strength gradually deteriorated after 35 seconds and up to 60 seconds (the longest time interval measured). The vortices at a time 60 seconds after they had been shed still maintained a large amount of circulation. The velocity distributions showed no indication of a disturbance other than that produced by the trailing vortices.

The vortices were photographed in an attempt to study the general pattern of the vortex filaments. The photographs indicated that the vortex filaments did not remain straight but became very irregular because of atmospheric turbulence.

In an attempt to fly an airplane in the trailing wake of another airplane, the pilot found that it was very difficult to maintain a precise course. The disturbance resulting from the vortices was similar to severe turbulence.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., December 8, 1954.

REFERENCES

1. Anon.: Big Plane Turbulence Can Cause a Flight Hazard. Safety Suggestions No. 8, Beech Aircraft Corp., c.1952.

2. Millikan, Clark B.: Aerodynamics of the Airplane. John Wiley & Sons, Inc., 1941, pp. 28-36.

3. Lamb, Horace: Hydrodynamics. Reprint of sixth ed. (first American ed.), Dover Publications, 1945, p. 592.

4. Spreiter, John R., and Sacks, Alvin H.: The Rolling Up of the Trailing Vortex Sheet and Its Effect on the Downwash Behind Wings. Jour. Aero. Sci., vol. 18, no. 1, Jan. 1951, pp. 21-32, 72.

TABLE I.- DIMENSIONS OF TEST AIRPLANES

Airplane used to generate vortices:	
Weight, lb	8,800
Wing area, sq ft	227.3
Wing span, ft	37.31
Airplanes used to probe the vortices:	
Airplane used to obtain data presented in figs. 7, 8(a), and 8(e):	
Weight, lb	13,480
Wing area, sq ft	237.6
Wing span, ft	38.83
Distance from angle-of-attack vane to center of gravity, ft	23
Airplane used to obtain data presented in figs. 8(b), (c), (d), (f), (g), and (h):	
Weight, lb	16,400
Wing area, sq ft	294
Wing span, ft	41.6
Distance from angle-of-attack vane to center of gravity, ft	22.5

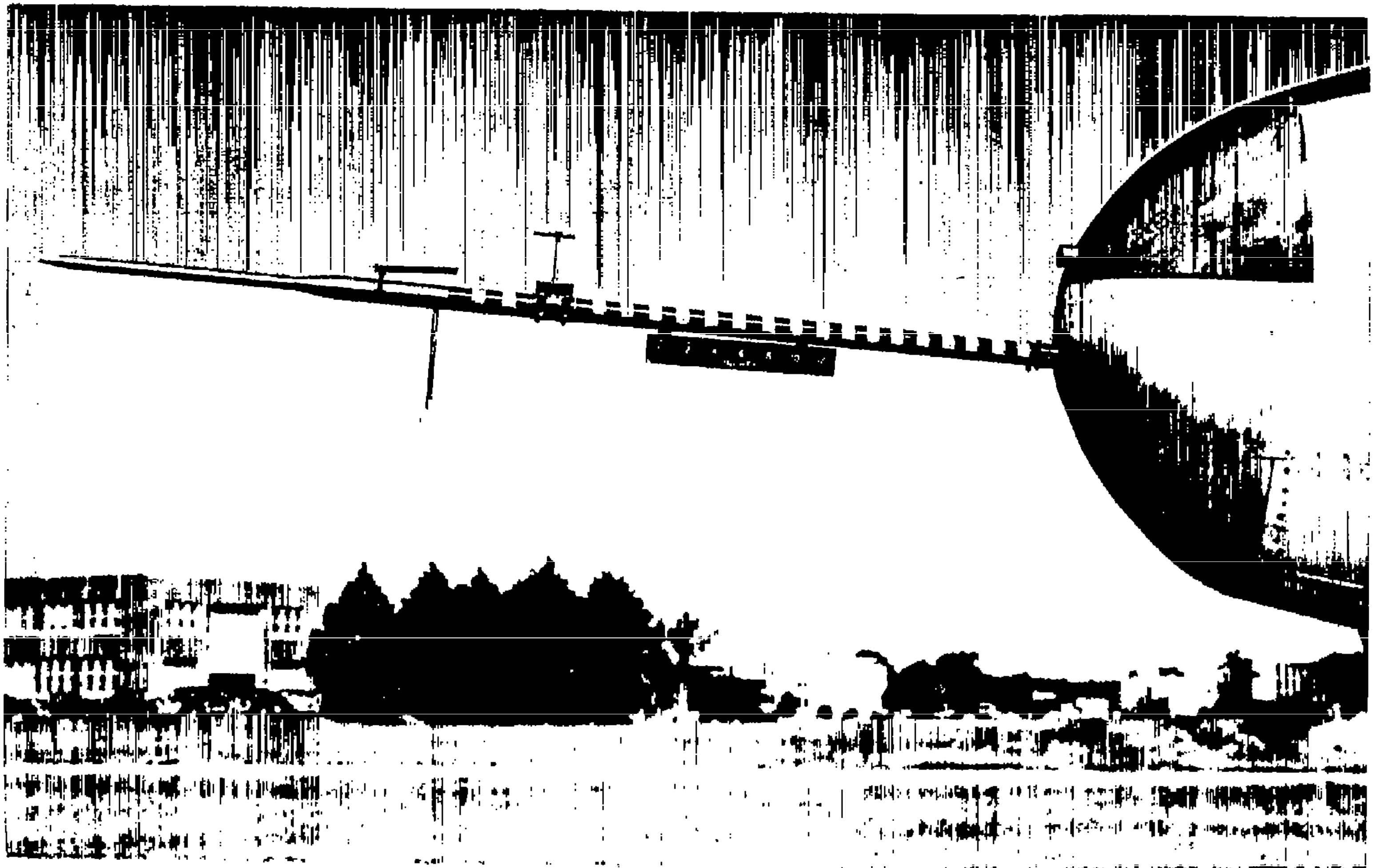

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Figure 1.- Installation of nose boom showing airspeed head, angle-of-attack vane, and total-pressure tube.

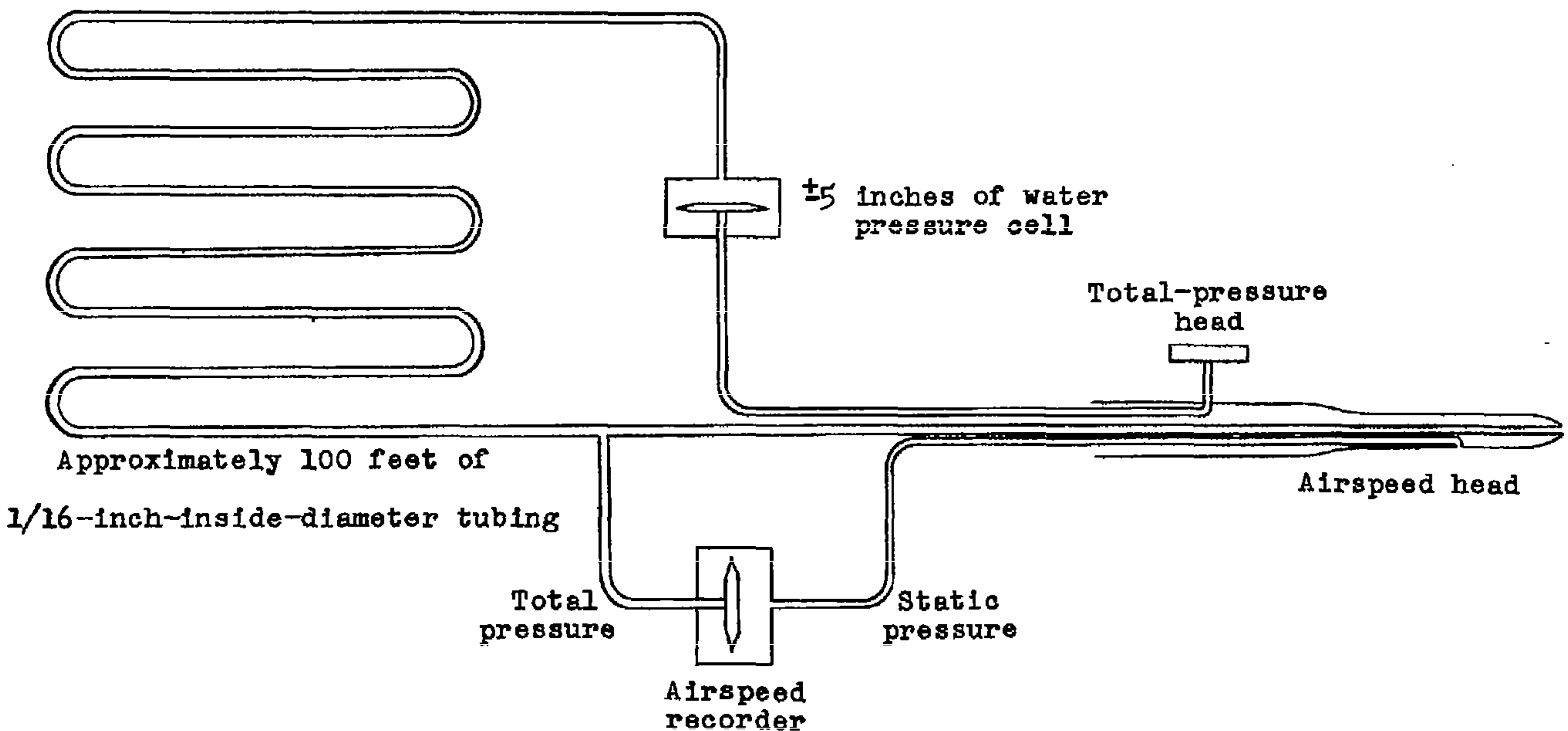

Figure 2.- Schematic drawing of airspeed-measuring system and the sensitive total-pressure-tube instrumentation.

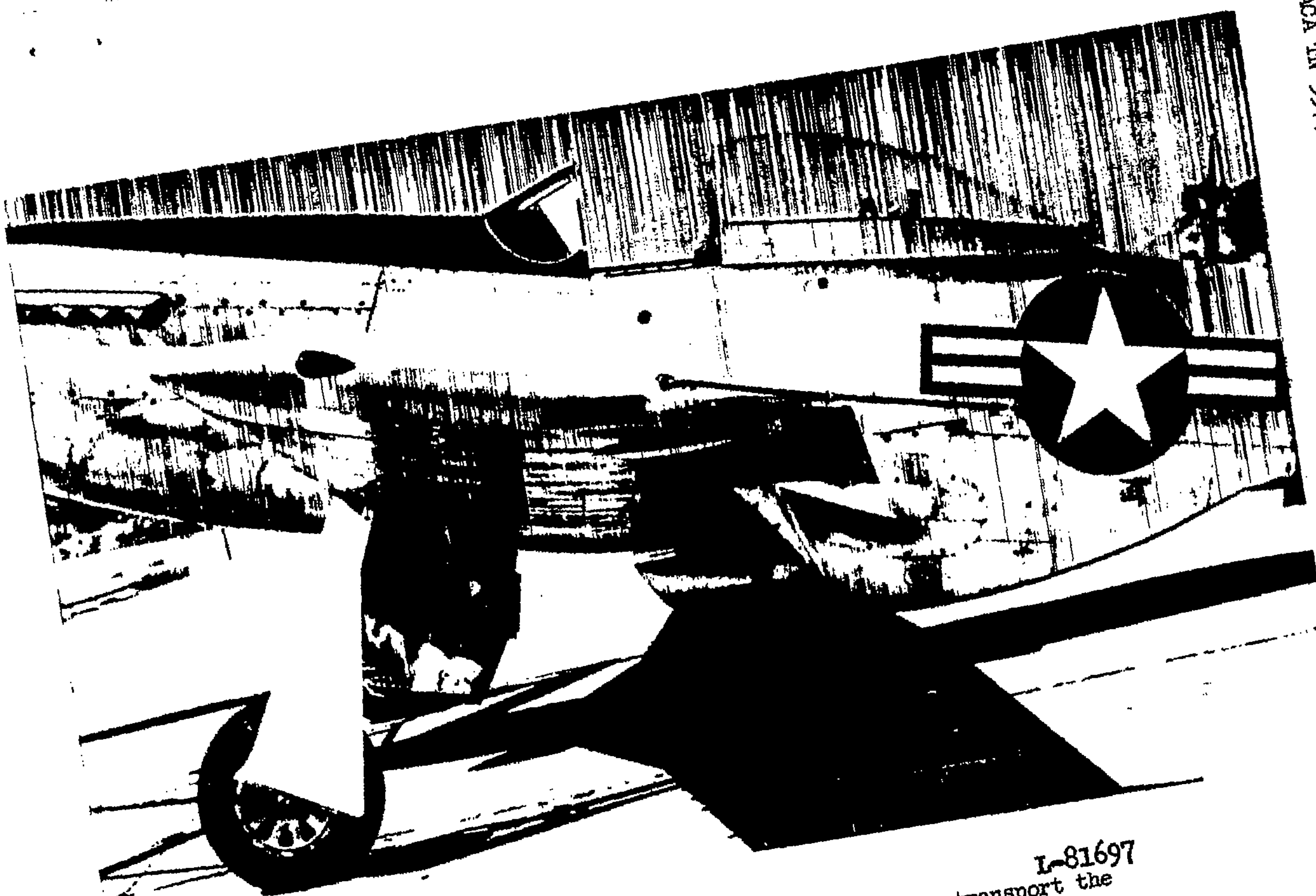

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Figure 3.- Wing-tip installation of the tube used to transport the smoke-generating fluid into the trailing vortex.

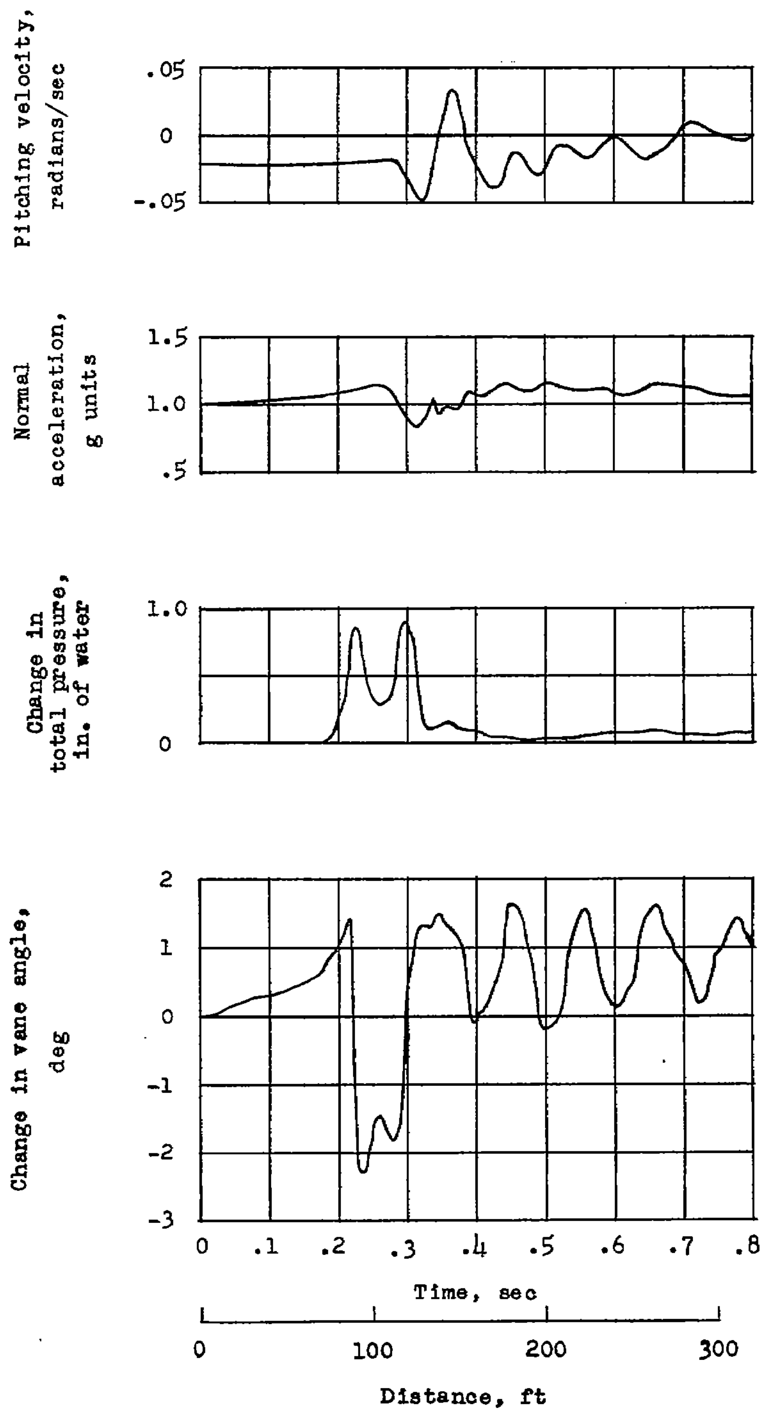


Figure 4.- Typical time history of the change in angle of attack, change in total pressure, normal acceleration, and pitching velocity as the airplane passed through the trailing vortices 38 seconds after the vortices had been shed. $V = 398$ ft/sec.

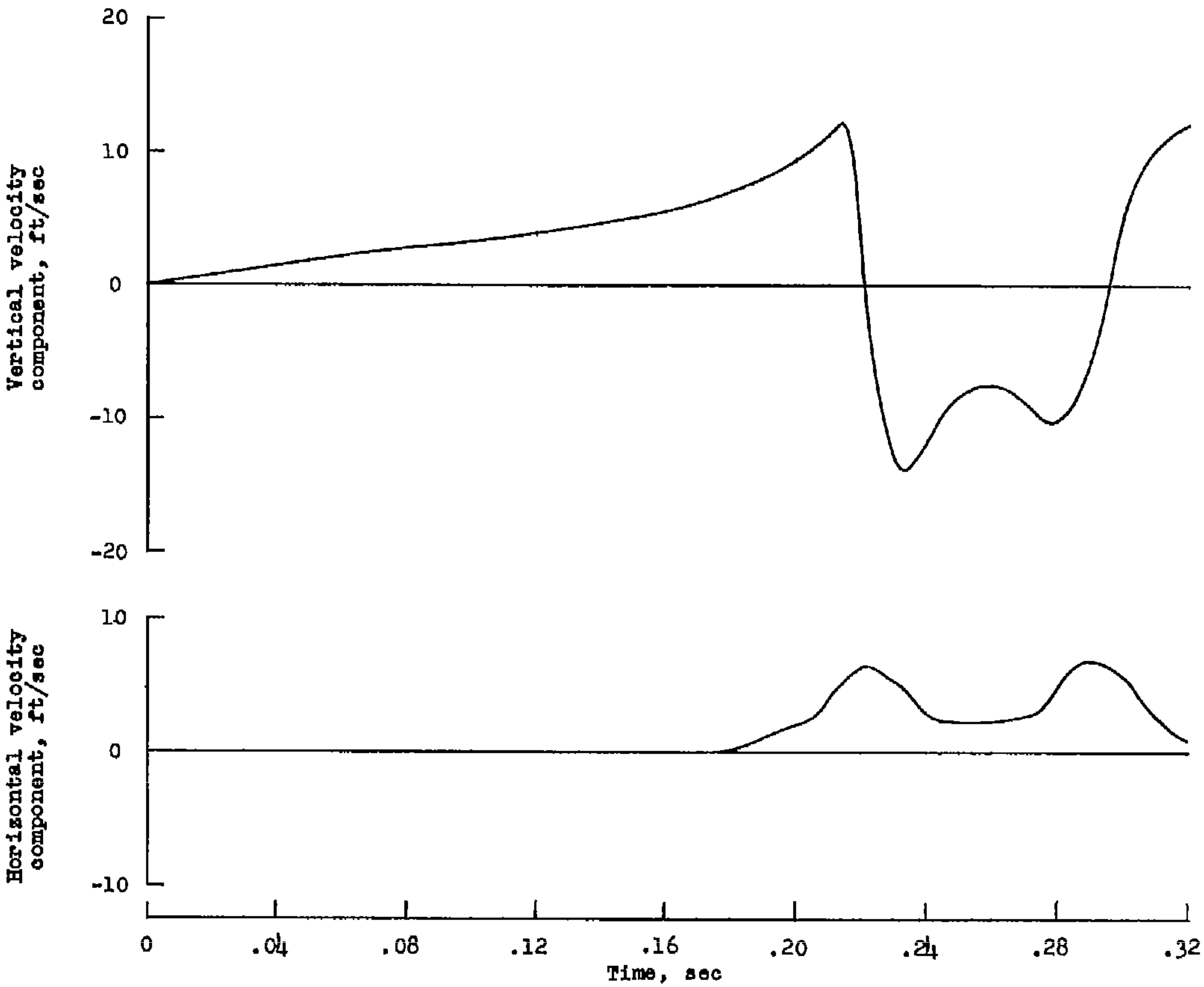


Figure 5.- Time history of the vertical and horizontal velocity components of the vortices obtained from figure 4.

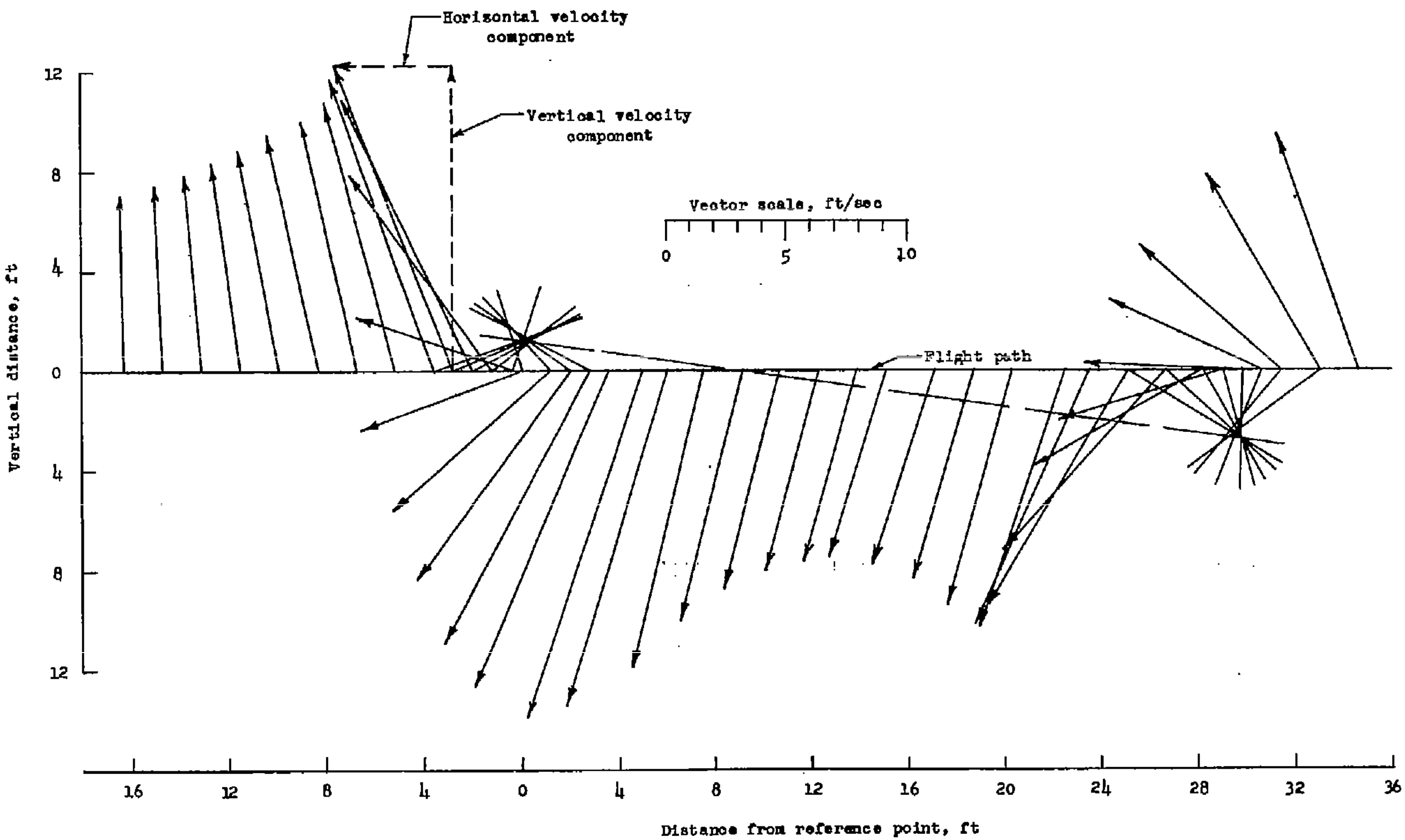


Figure 6.- Vector plot of the vertical and horizontal velocity components shown in figure 5 as a function of the distance from the reference point.

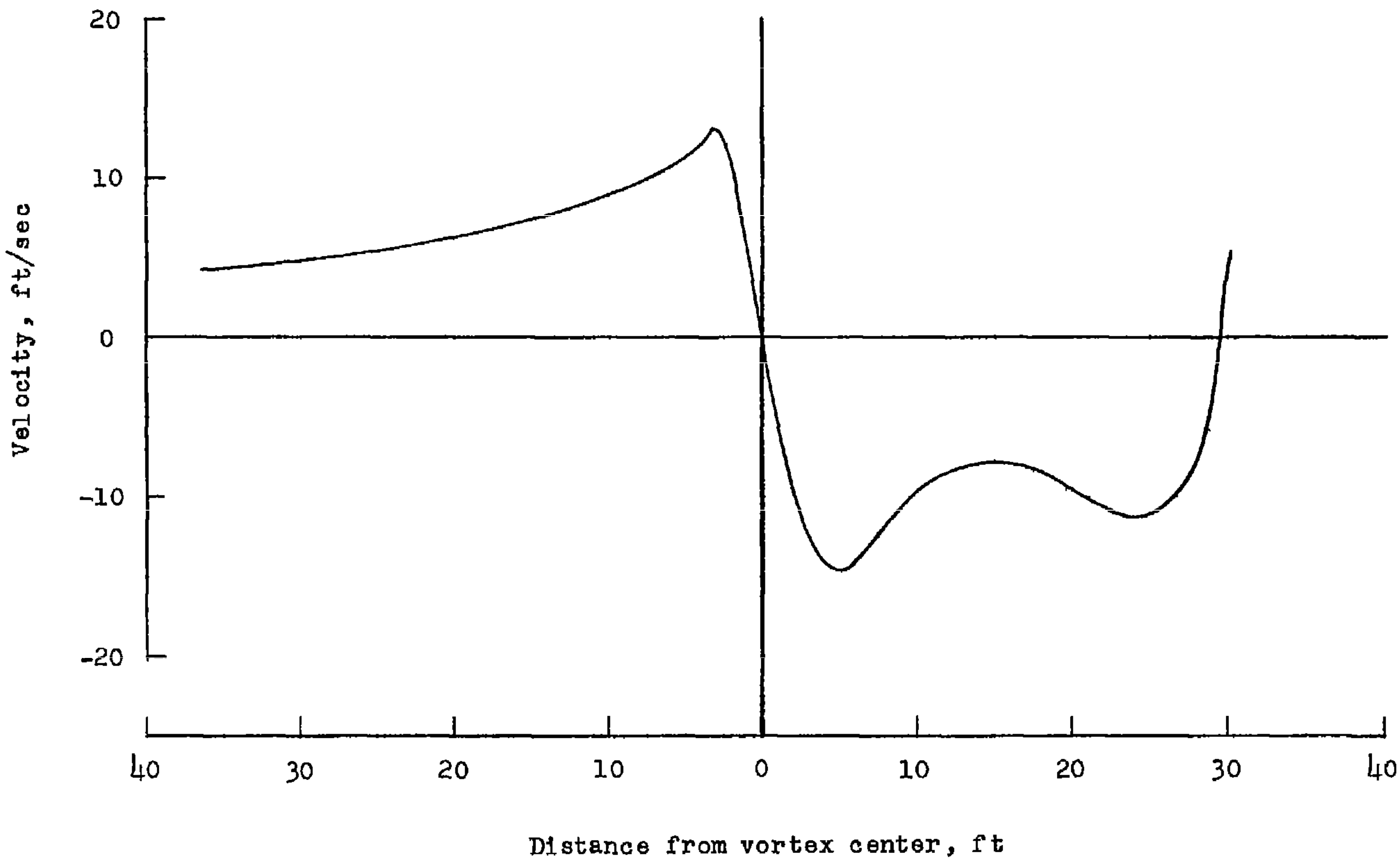
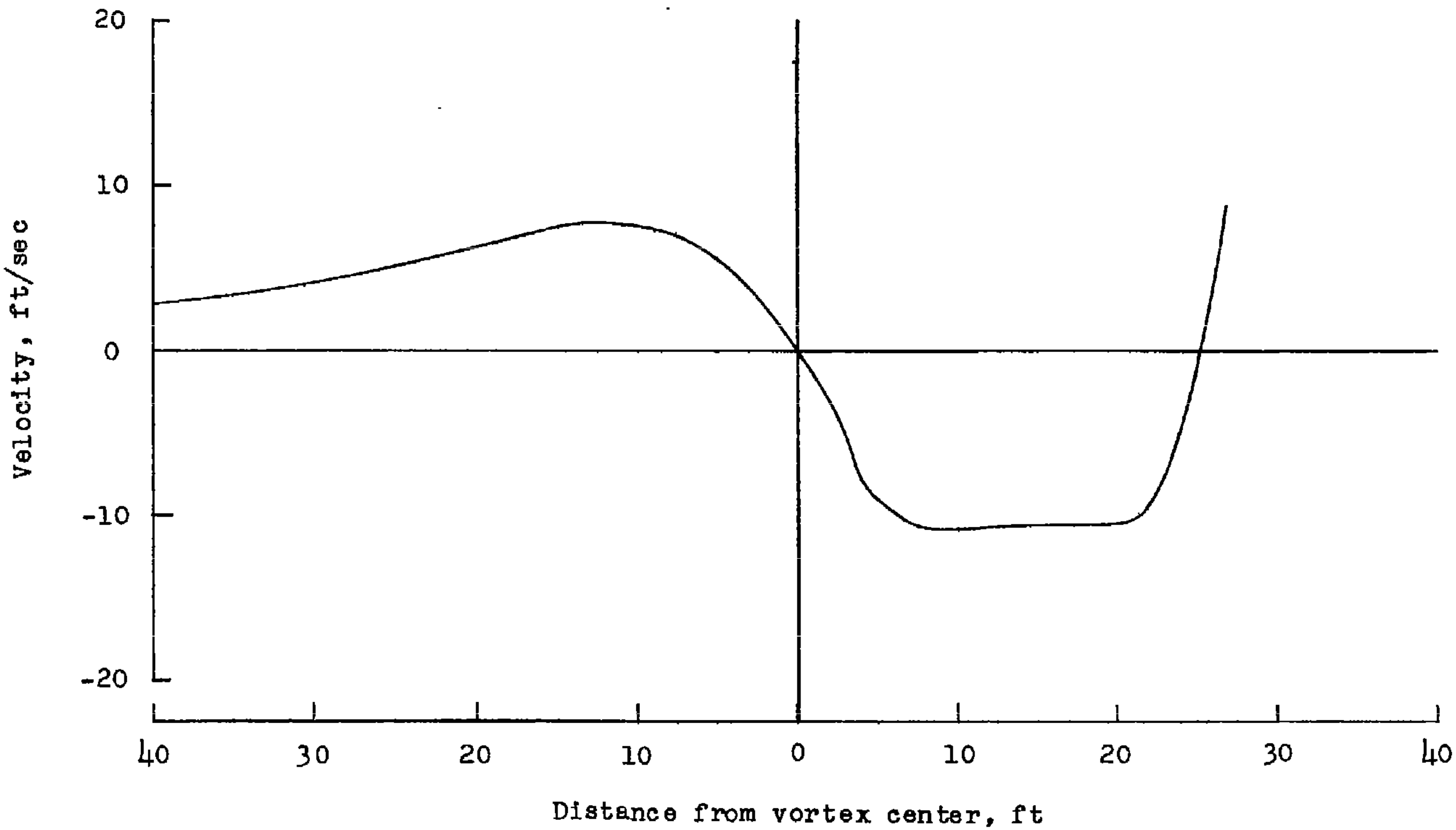
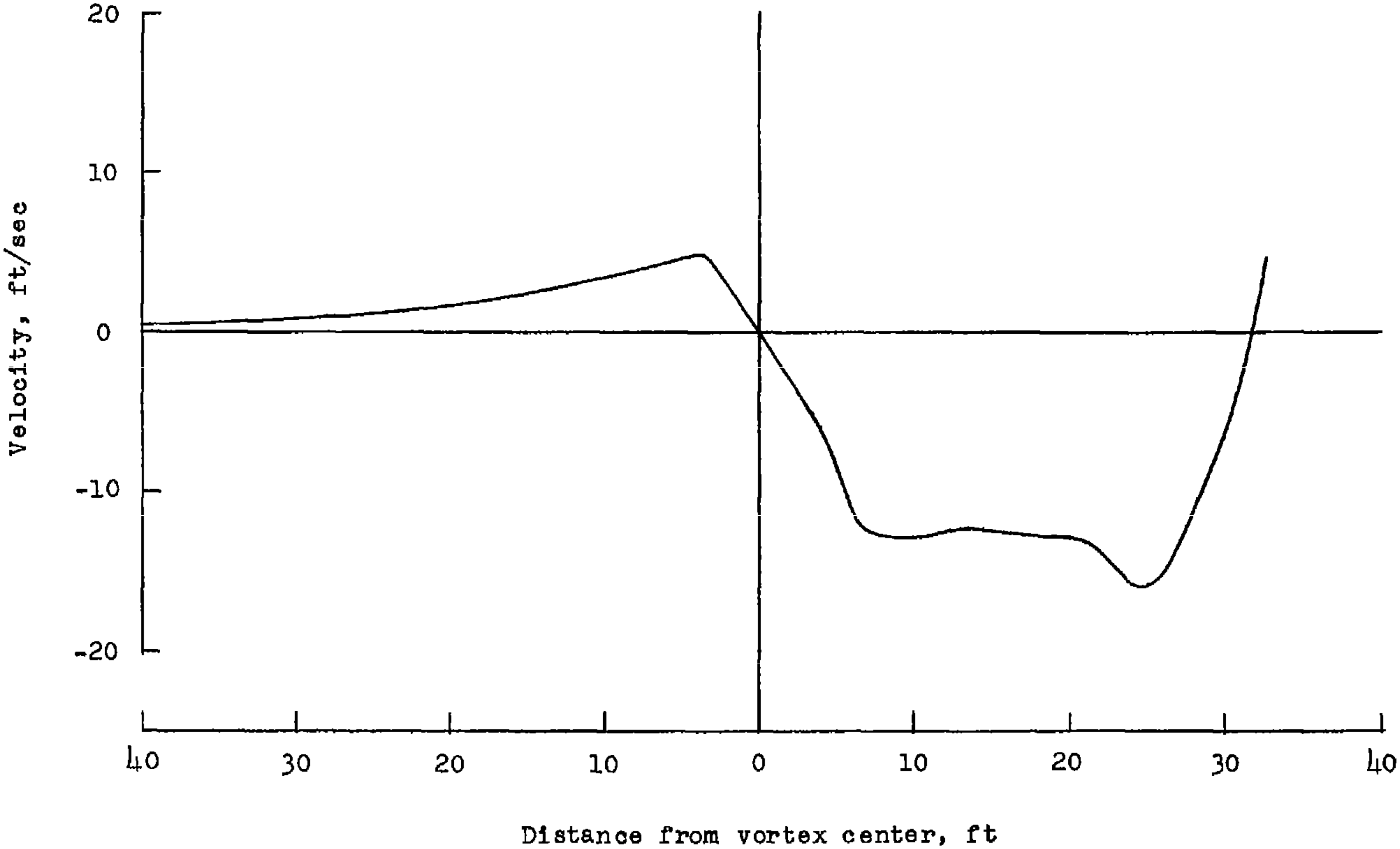


Figure 7.- Velocity distribution in the trailing vortices obtained from figure 6. Data obtained 38 seconds after the vortices had been shed.



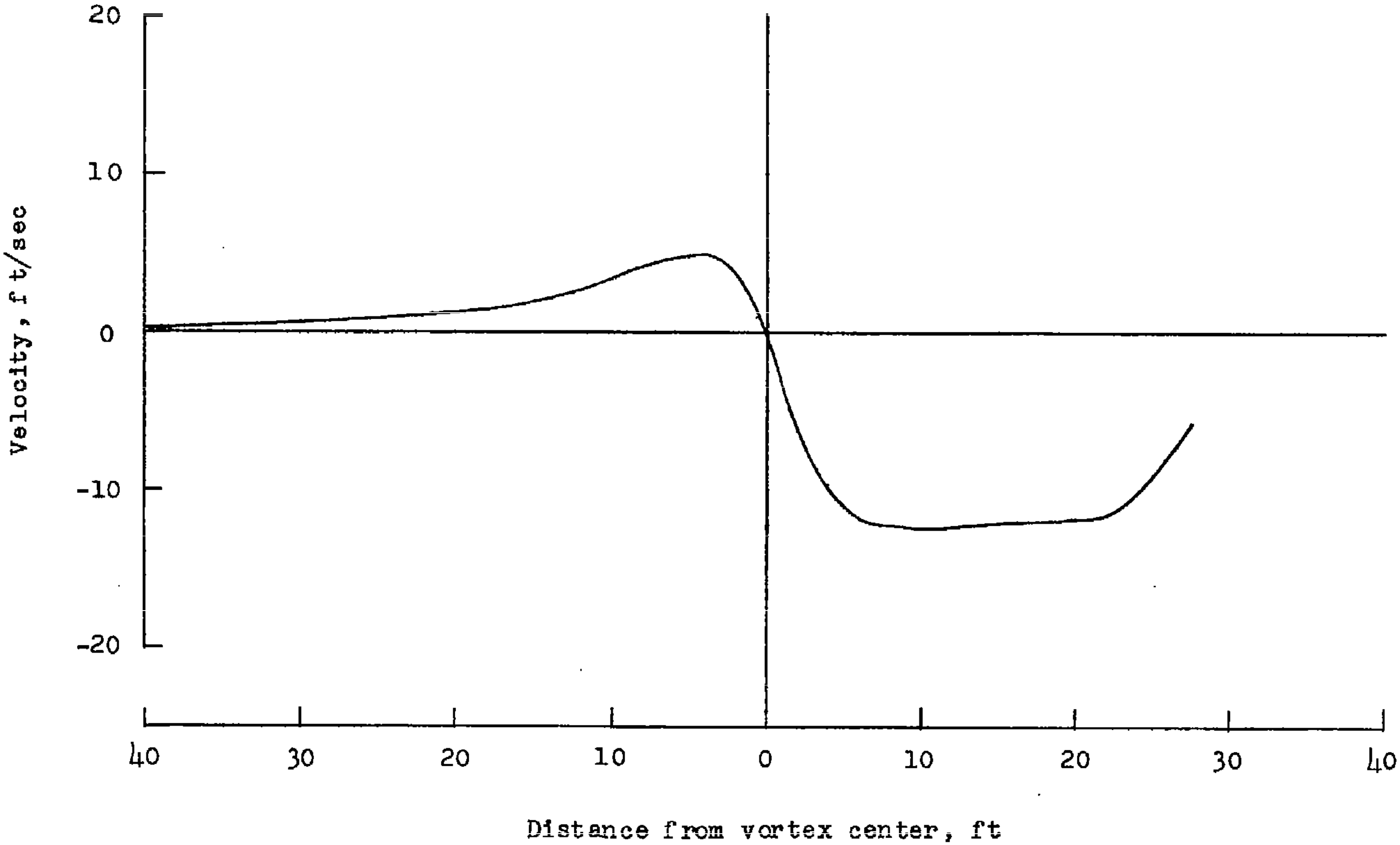
(a) 10 seconds.

Figure 8.- Velocity distribution in the trailing vortices at various lengths of time after the vortices were shed.



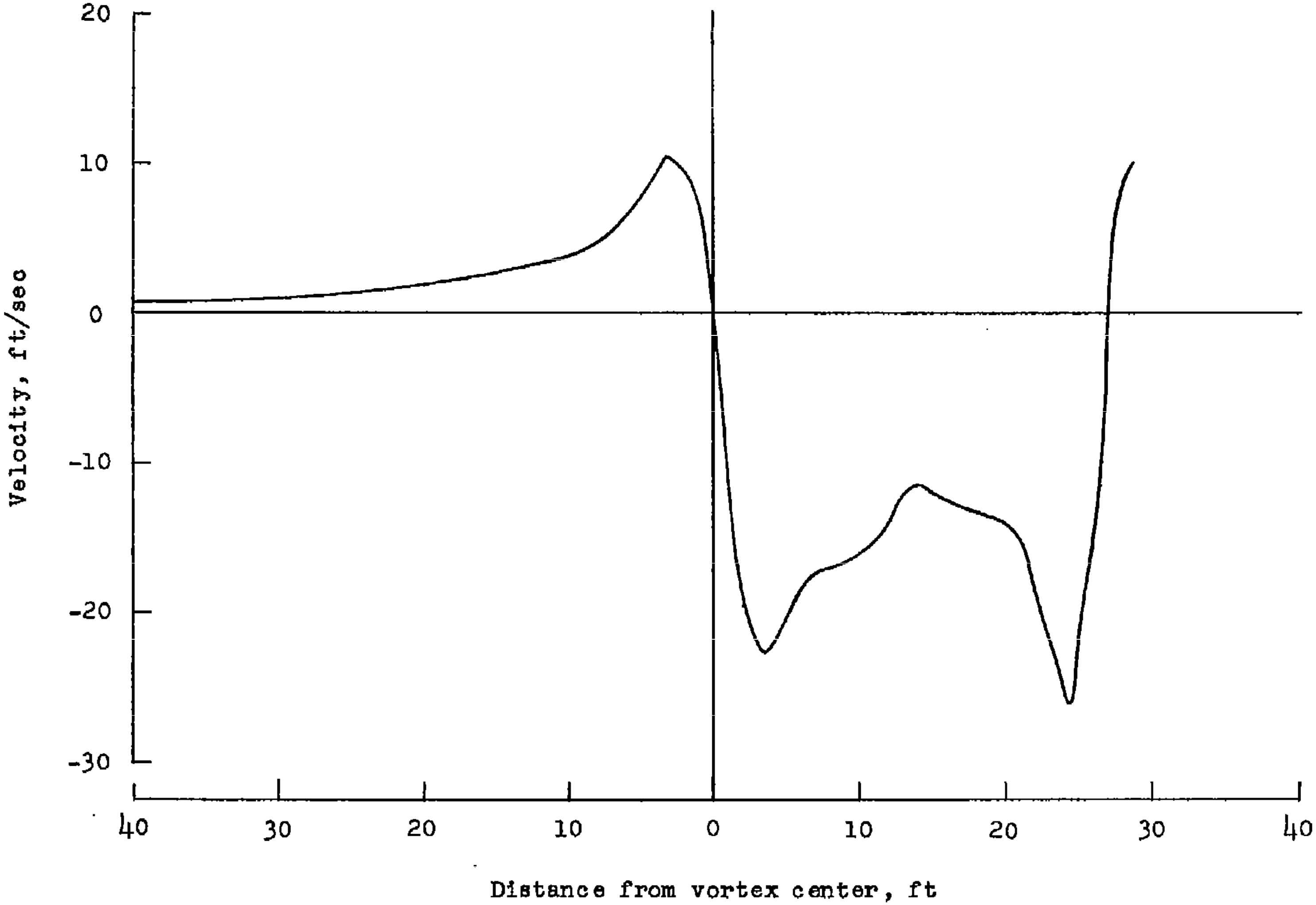
(b) 15 seconds.

Figure 8.- Continued.



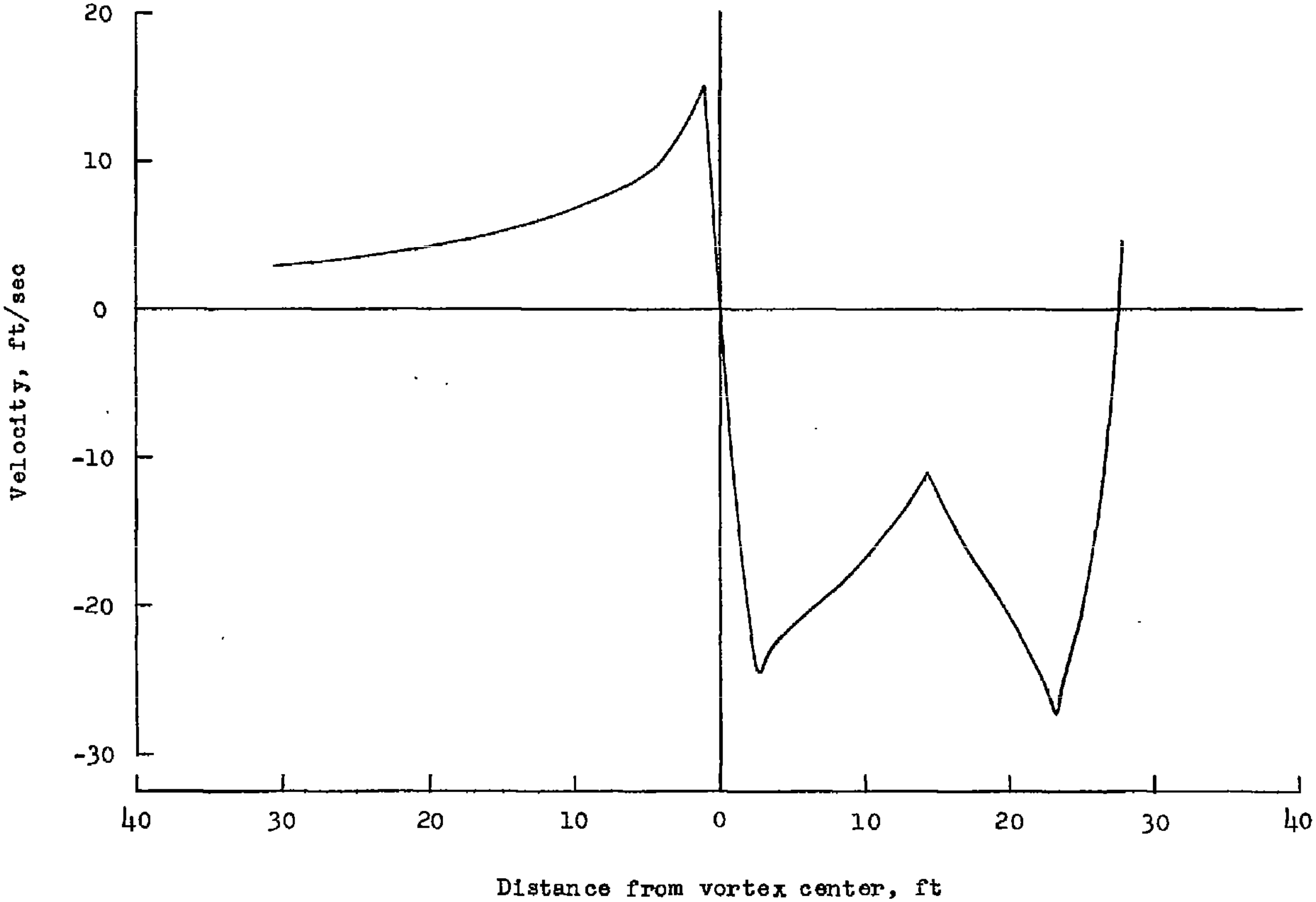
(c) 20 seconds.

Figure 8.- Continued.



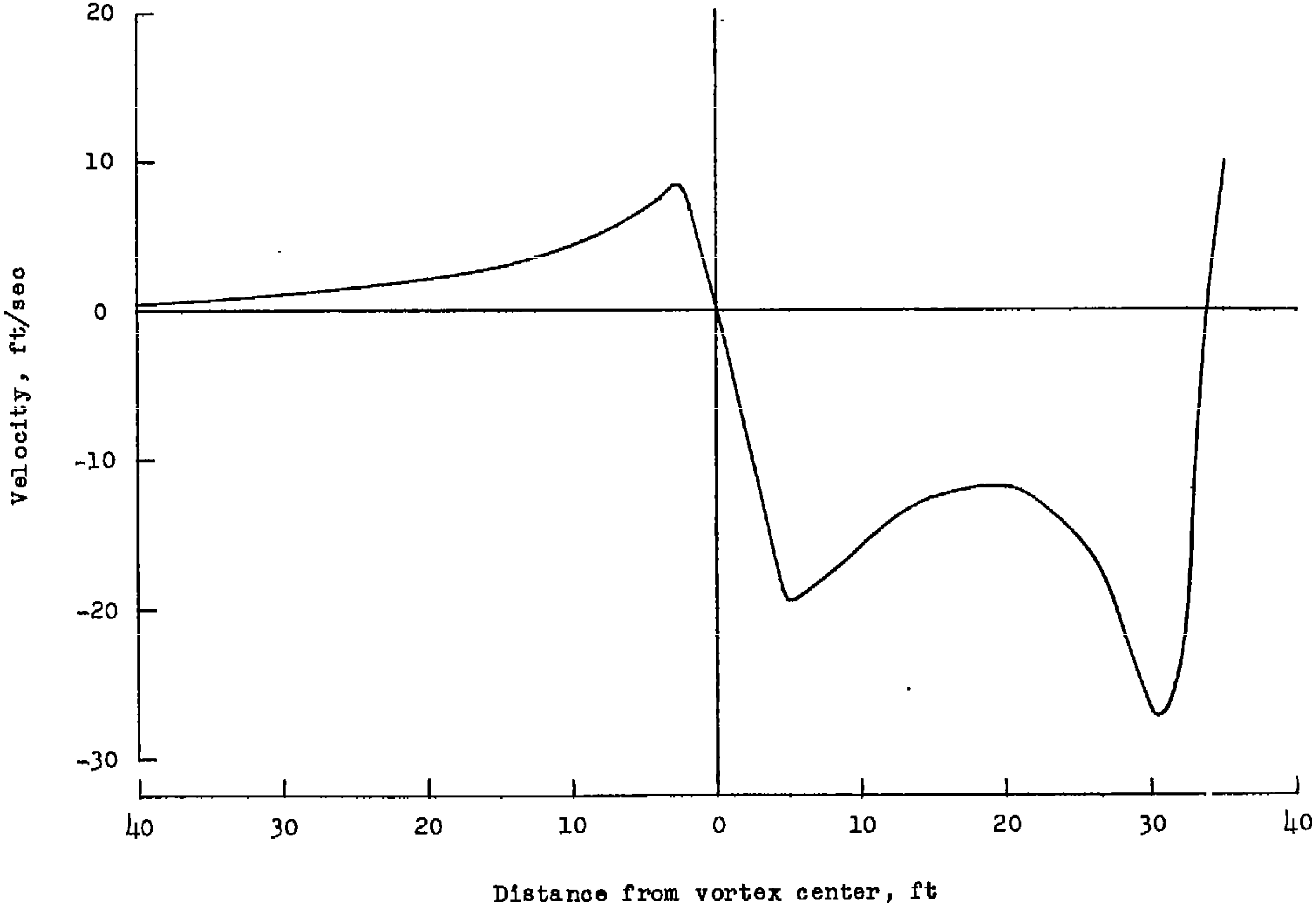
(d) 23 seconds.

Figure 8.- Continued.



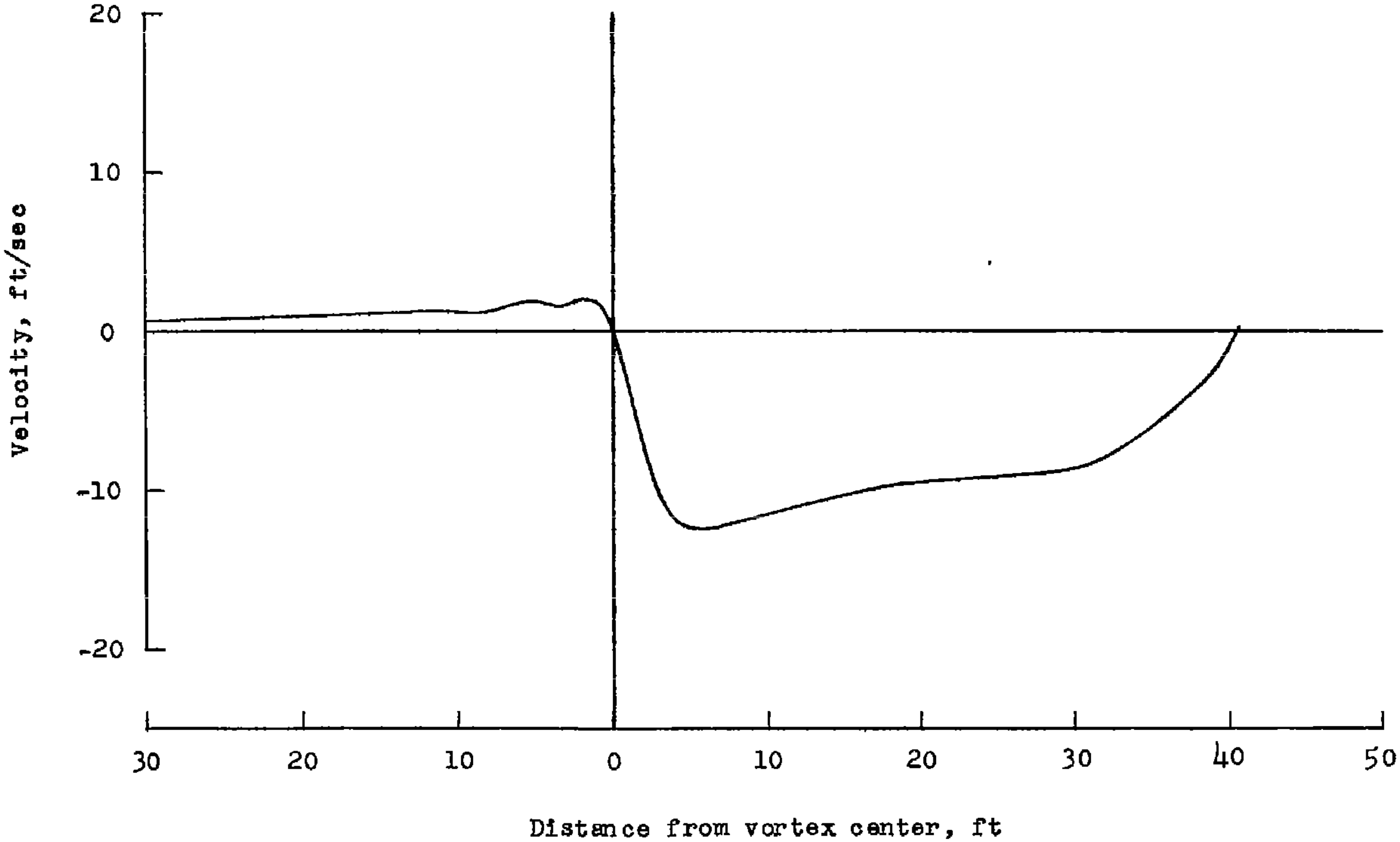
(e) 33 seconds.

Figure 8.- Continued.



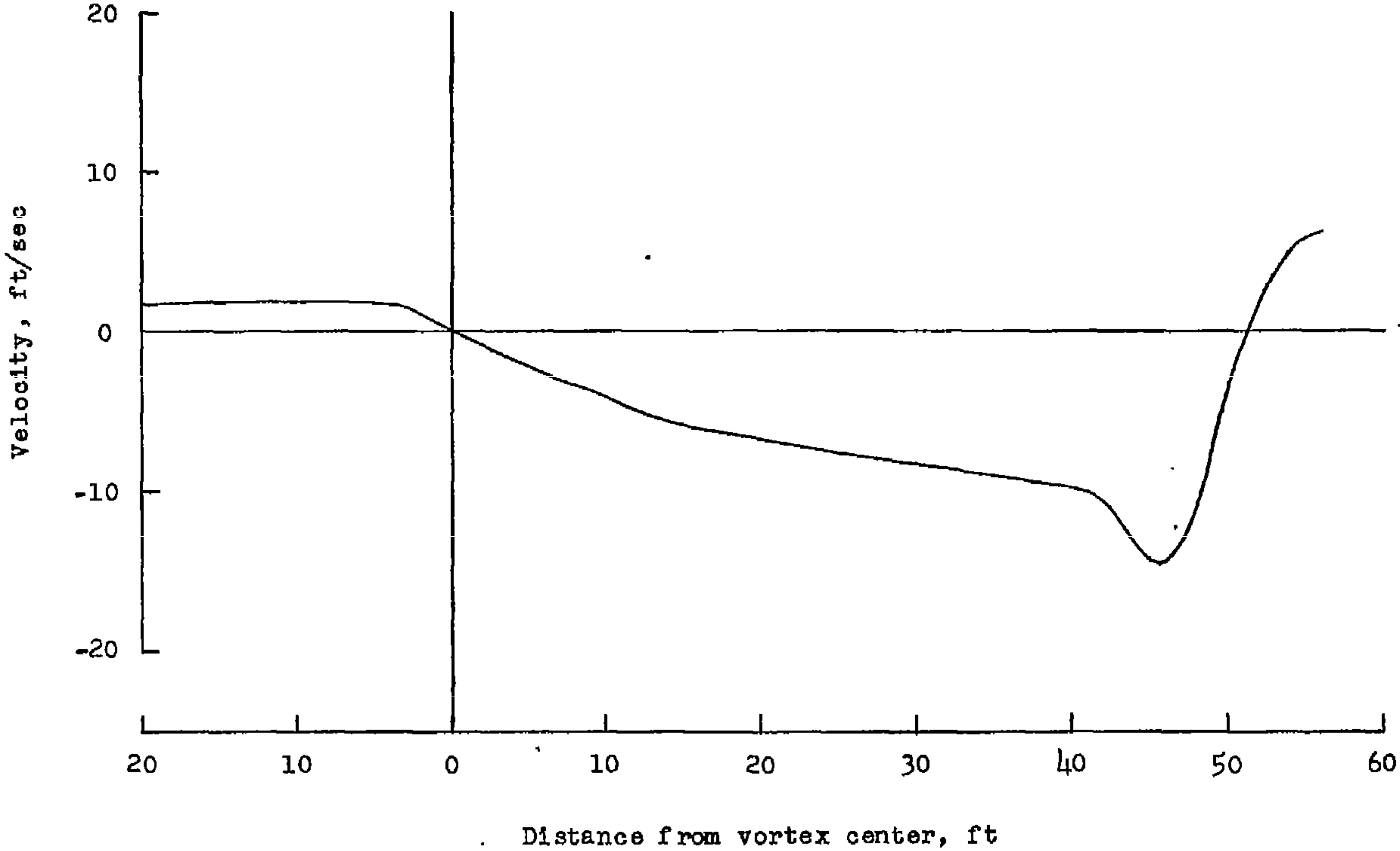
(f) 45 seconds.

Figure 8.- Continued.



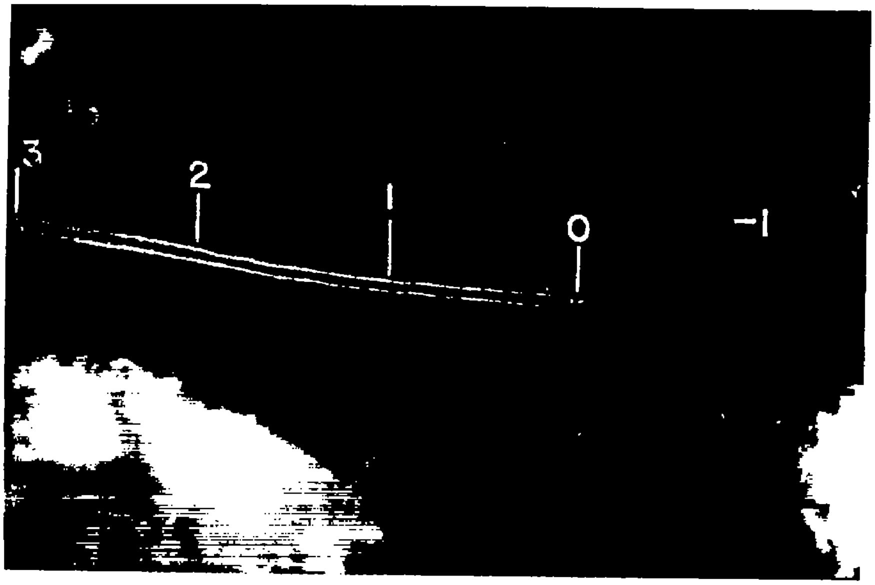
(g) 58 seconds.

Figure 8.- Continued.

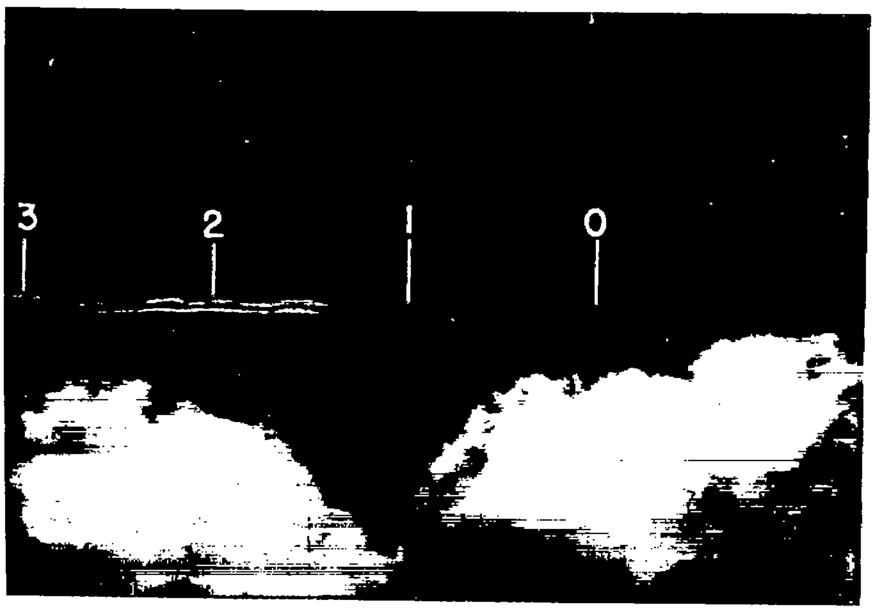


(h) 60 seconds.

Figure 8.- Concluded.



Sequence (a).



Sequence (b).

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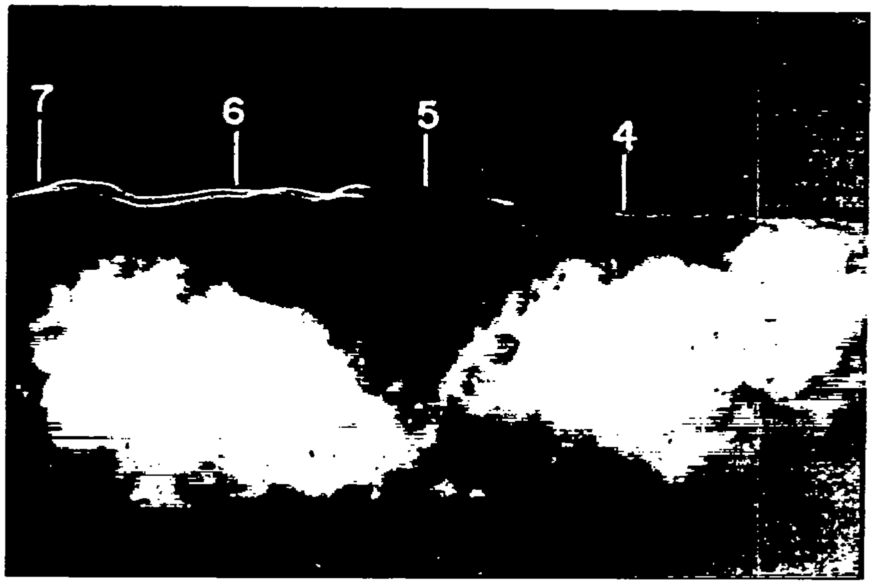
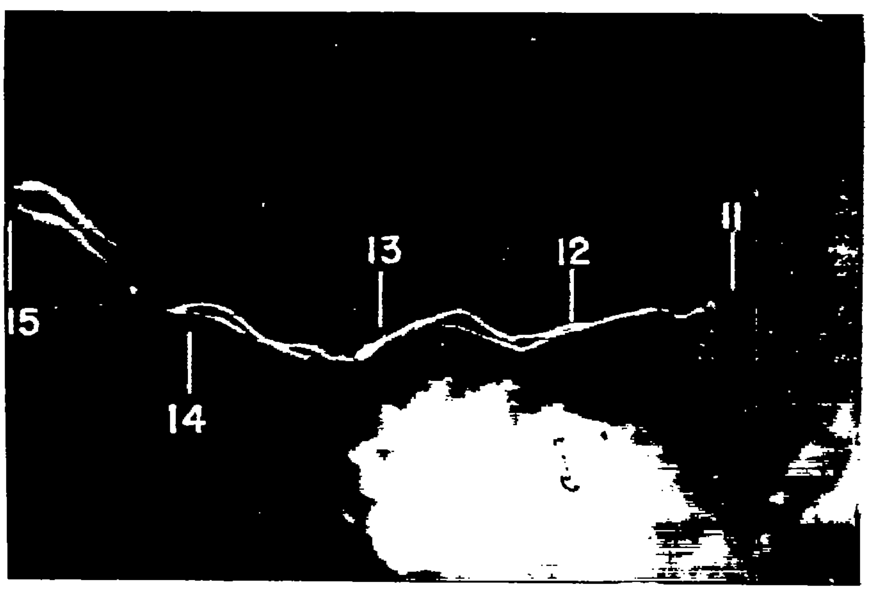
Figure 9.- Time sequences of the trailing vortices of the test airplane in turbulent air at an altitude of 1,000 feet. Scales indicate time in seconds after the vortices had been shed. Pictures taken from the ground.

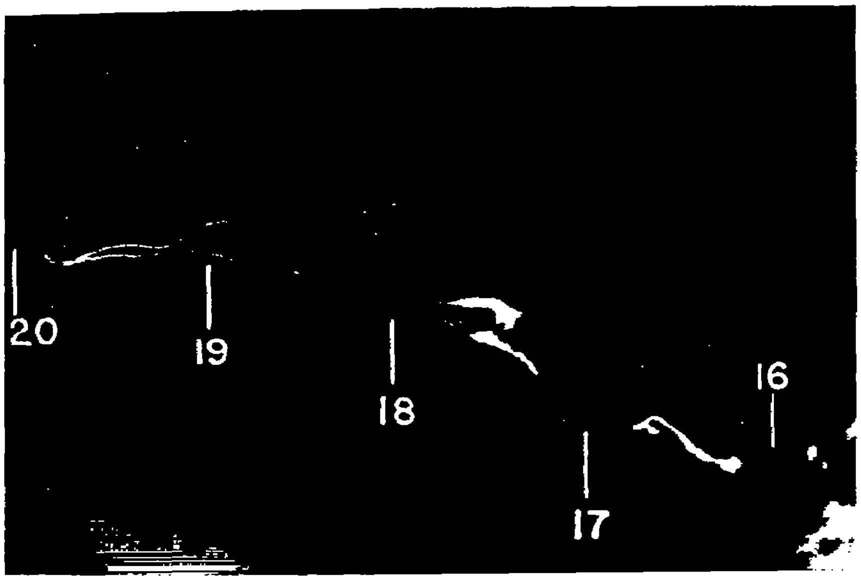


Sequence (b).- Continued.



Sequence (b).- Continued.

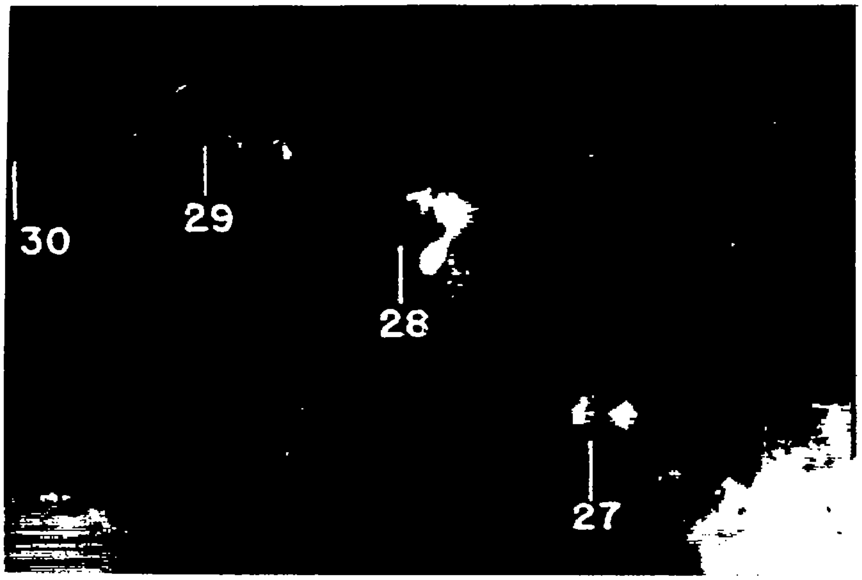
Figure 9.- Continued. L-86521



Sequence (b).- Continued.

Sequence (b).- Continued.

Figure 9.- Continued. L-87498



Sequence (b).- Concluded.

Figure 9.- Concluded. L-87499

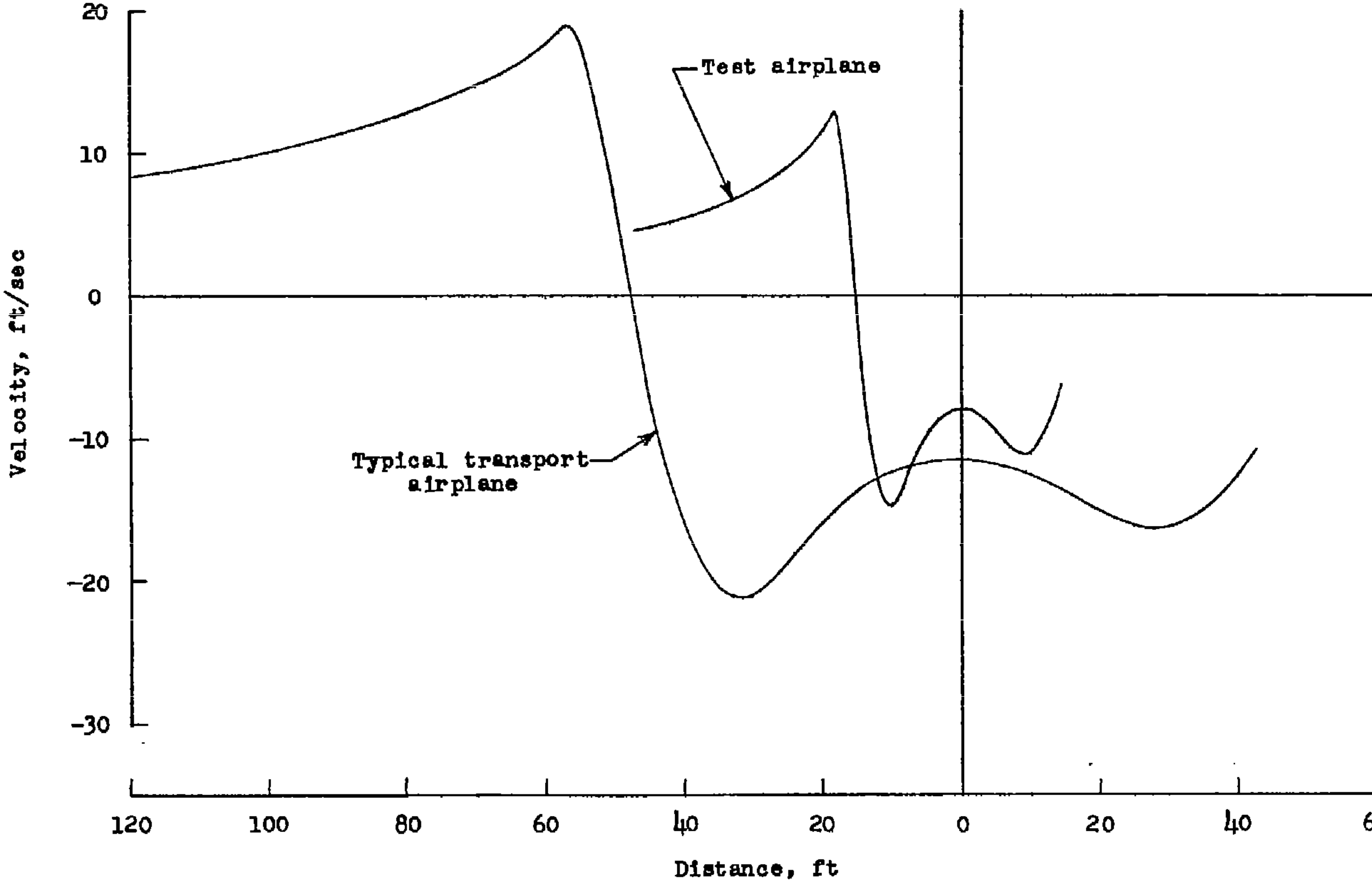


Figure 10.- Comparison of the velocity distribution in the trailing vortices of the test airplane with that calculated for a typical transport airplane.

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